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Mazdoor Kisan Shakti Sangathan

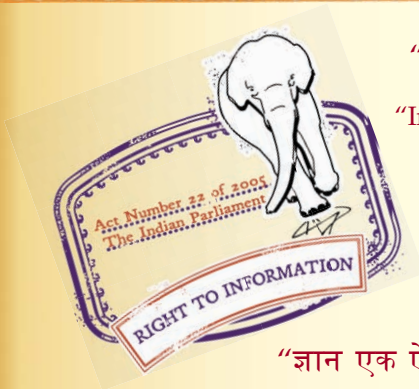
“The Right to Information, The Right to Live”

“पुराने को छोड़ नये के तरफ”

Jawaharlal Nehru

“Step Out From the Old to the New”

IS 14884 (2000): Mechanical Vibration and Shock - Vibration of Buildings - Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings [MED 28: Mechanical Vibration and Shock]



“ज्ञान से एक नये भारत का निर्माण”

Satyanarayan Gangaram Pitroda

“Invent a New India Using Knowledge”



“ज्ञान एक ऐसा खजाना है जो कभी चुराया नहीं जा सकता है”

Bhartrhari—Nitiśatakam

“Knowledge is such a treasure which cannot be stolen”

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REAFFIRMED

2005

IS 14884 : 2000

ISO 4866 : 1990

भारतीय मानक

यांत्रिक कंपन और प्रघात — इमारतों का कंपन —
कंपन मापन के दिशानिर्देश तथा इमारतों पर
उनके प्रभाव का मूल्यांकन

Indian Standard

MECHANICAL VIBRATION AND SHOCK —
VIBRATION OF BUILDINGS — GUIDELINES
FOR THE MEASUREMENT OF VIBRATIONS
AND EVALUATION OF THEIR EFFECTS
ON BUILDINGS

ICS 17.160

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

October 2000

Price Group 10

NATIONAL FOREWORD

This Indian Standard which is identical with ISO 4866 :1990 'Mechanical vibration and shock — Vibration of buildings — Guidelines for the measurement of vibrations and evaluation of their effects on buildings' issued by the International Organization for Standardization (ISO) was adopted by the Bureau of Indian Standards on the recommendations of the Mechanical Vibration and Shock Sectional Committee and approval of the Mechanical Engineering Division Council.

The text of ISO standard has been approved as suitable for publication as Indian Standard without deviations. In the adopted standard, certain conventions are, however, not identical to those used in Indian Standards. Attention is especially drawn to the following:

- a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
- b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a full point (.) as the decimal marker.

Amendment 1 to the above International Standard has been printed at the end.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their place are listed below along with their degree of equivalence for the editions indicated:

<i>International Standard</i>	<i>Corresponding Indian Standard</i>	<i>Degree of Equivalence</i>
ISO 2041 : 1990	IS 11717 : 2000 Vocabulary on vibration and shock (<i>first revision</i>)	Identical
ISO 2631-2 : 1989	IS 13276 (Part 2) : 1992 Evaluation of human exposure to whole body vibrations : Part 2 Continuous and shock induced vibrations in buildings (1-80 Hz)	do
ISO 5348 : 1987	IS 14883 : 2000 Mechanical vibration and shock : Mechanical mounting of accelerometers	do

The concerned technical committee has reviewed the provisions of the following International Standards referred in this adopted standard and has decided that they are acceptable for use in conjunction with this standard:

<i>International Standard</i>	<i>Title</i>
ISO 4356 : 1977	Bases for the design of structures – Deformations of buildings at the serviceability limit states
IEC 68-2-27 : 1987	Environmental testing – Part 2 : Tests – Test Ea and Guidance : Shock

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

**AMENDMENT NO. 2 AUGUST 2007
TO
IS 14884 : 2000/ISO 4866 : 1990 MECHANICAL VIBRATION AND SHOCK —
VIBRATION OF BUILDINGS — GUIDELINES FOR THE MEASUREMENTS OF
VIBRATIONS AND EVALUATION OF THEIR EFFECTS ON BUILDINGS**

[Page 17, Annex D (see also Amendment No.1)] — Insert the following Annex as Annex E and renumber the existing Annex E as Annex F:

Annex E (informative)

Vibrational interaction between the foundation of a structure and the soil

E.1 General

When vibration measurements cannot be made on the foundation of a structure or inside a building, ISO 4866 allows that measurements be made on the ground surface outside. It may also be necessary to predict the response of a building not yet constructed. In both cases there is a need to understand the dynamic interaction between a building and the ground.

In the first case, the most suitable position outside the building for measurement and the relationship between the signal at that position and that on the building foundation need to be established.

In the second case, the response of the foundation of the building may be expected to follow closely the motion of the ground in contact with the foundation unless interaction is significant. This annex seeks to indicate the nature of such an interaction and suggests procedures which allow it to be taken into account.

Figure E.1 illustrates the notation which will be used in this annex in terms of the peak amplitude, u , of a travelling wave passing across a foundation (u can be the displacement, velocity or acceleration amplitude of the sinusoidal wave). Free-field amplitude is denoted by u_0 , amplitude in the base of the foundation by u_F , amplitude at an arbitrary position in the structure by u_{st} , and on the soil surface near an existing building by u_N . Far from the structure, $u_N = u_0$. Soil-structure interaction analysis is concerned generally with the relationship between free-field motion and structure motion, that is u_{st}/u_0 and, in particular, $u_F/u_0 = r_0$. The important ratio $u_F/u_N = r_N$ is given by the more sophisticated procedures which also address the problem of soil response involving the variation of vibration amplitude with depth.

AMENDMENT 1

Page 17

Add the following annex as annex D and change the present annex D to annex E.

Page 18

Add references [24] to [38] to annex E.

Annex D

(informative)

Predicting natural frequencies and damping of buildings

Introduction

ISO 4866:1990 specifies methods of measuring building response including fundamental natural frequencies. When direct measurements cannot be made or are limited in usefulness by high damping, sub-component resonances or other practical problems, it becomes necessary to estimate natural frequency and damping values.

This annex offers guidance on the ways in which the fundamental natural frequency and associated damping value may be assessed. It draws attention to the uncertainties involved which should be taken into account wherever an estimation of fundamental natural frequencies of a building is used in measuring or evaluation procedures.

D.1 Predicting natural frequencies of tall buildings using empirical methods

There are many empirical formulae for predicting the frequency f , or period T , of the fundamental translation mode; of these the simplest is $f = 10/N$ Hz (i.e. $T = 0,1N$ s), where N is the number of storeys. Various other formulae are given in the codes of different countries and these can be grouped into three categories:

$$T = k_1 H \quad \dots \text{D.1}$$

where

H is the height, in metres;

T is the period, in seconds;

k_1 ranges from $0,14 \text{ s m}^{-1}$ to $0,03 \text{ s m}^{-1}$

(references [24] to [27]).

$$T = k_2 H \sqrt{D} \quad \dots \text{D.2}$$

where

D is the width parallel to the force, in metres;

k_2 ranges from $0,087 \text{ s m}^{-3/2}$ to $0,109 \text{ s m}^{-3/2}$

(references [25] and [28]).

$$T = k_3 H \sqrt{D} \text{ func}(H, D, I) \quad \dots \text{D.3}$$

(see, for example, reference [29]).

NOTE 1 k_1 has the units s m^{-1} ; k_2 has the units $\text{s m}^{-3/2}$.

A later study [30], considering a sample of 163 rectangular-plan buildings, recommended $f = 46/H$ Hz·m (i.e. $T = 0,022H \text{ s m}^{-1}$) for the fundamental translation mode, $f = 58/H$ Hz·m for the orthogonal fundamental translation mode and $f = 72/H$ Hz·m for the fundamental torsional mode (sample size of 63 buildings).

NOTE 2 These formulae for f are empirical. They may also be considered as numerical value equations yielding values of f in hertz when values of H in metres are inserted, for instance $f = 46/H$.

Figure D.1 shows the resulting fit of the curve $f = 46/H$ Hz·m to the data and it can be appreciated that large errors are likely to be encountered. It can be seen that errors of $\pm 50\%$ are not uncommon, and this is typical of the accuracy which can be expected using empirical formulae. Based on measured data, it appears that the mode shapes of the fundamental modes of tall buildings can be reasonably approximated by straight lines.

D.2 Predicting natural frequencies of tall buildings using computer-based methods

It has long been realised that comparatively large errors are likely to occur using the simple empirical formulae, but it has also been generally accepted that a satisfactory estimate of frequency can be obtained using one of the standard computer-based methods. However, buildings are complicated structures and it is not a simple task to create an accurate mathematical model; consequently it must be accepted that these models will only provide approximate predictions. In a study [30] examining published evidence, the correlation between computed frequencies and measured frequencies was actually considerably worse than the correlation between the frequencies predicted using $f = 46/H$ Hz·m and the measured values. This discrepancy can be attributed to inadequacies in modelling the real

properties of buildings. Predictions of fundamental frequencies should therefore be treated with caution.

Special methods have been developed for analysis of core buildings [31], shear buildings [32] and sway frame and frame buildings [33], but with any method it is important to check whether the method has been calibrated using a range of reliable experimental data and to understand what errors are likely to be encountered. If the method has not been proven, then accuracies greater than those obtained for empirical predictors should not be assumed. Only the fundamental frequencies have been discussed, but the predicted frequencies of higher frequency modes will suffer from similar or (more probably) greater errors. This means that, except for special cases where the mathematical model has been tuned to experimental results, predictions involving many calculated modes must be regarded as unreliable.

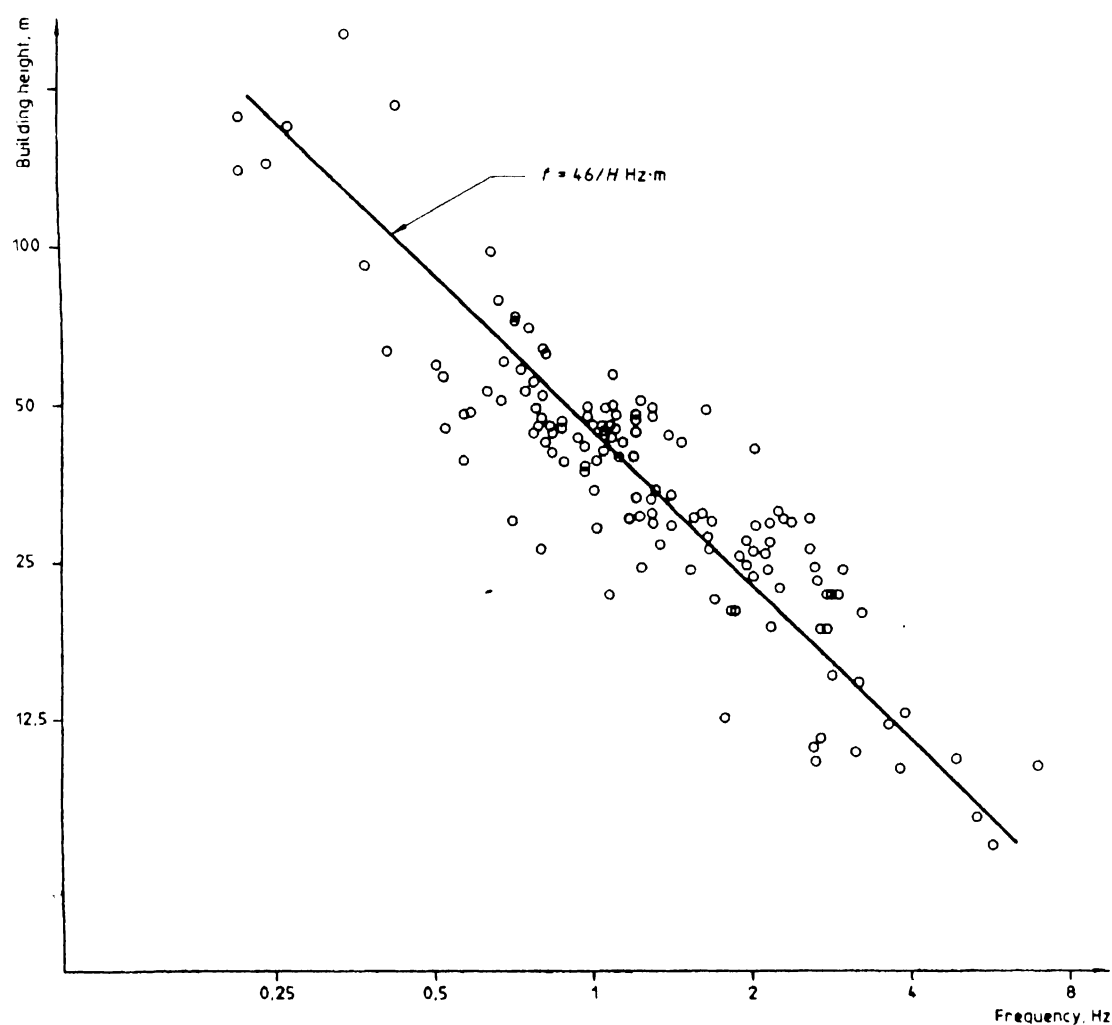


Figure D.1 — Plot of height versus fundamental frequency for 163 rectangular-plan buildings using logarithmic scales

D.3 Predicting damping values of tall buildings

The damping (or rate of energy dissipation) in any one mode limits the motion in that mode, and consequently to estimate the building response to a given load it is necessary to estimate or measure the amount of damping. No proven methods of predicting damping exist and the measured data show that damping values between 0,5 % and 2,1 % critical can occur (see figure D.2). Higher values may also be encountered in buildings where soil/structure inter-

action is significant. Simple steel frames are likely to have much lower damping. Methods of predicting damping have been developed (see refs. [34] and [35]) but, again, the expected accuracy is not quoted.

Figure D.2 shows a plot of damping versus building height for a selected sample of buildings [36]. It can be seen that large differences in damping can be obtained for orthogonal translation modes of the same building. Damping is partly a function of the construction procedures and workmanship involved and cannot be predicted accurately. Consequently, large errors in estimation must be anticipated.

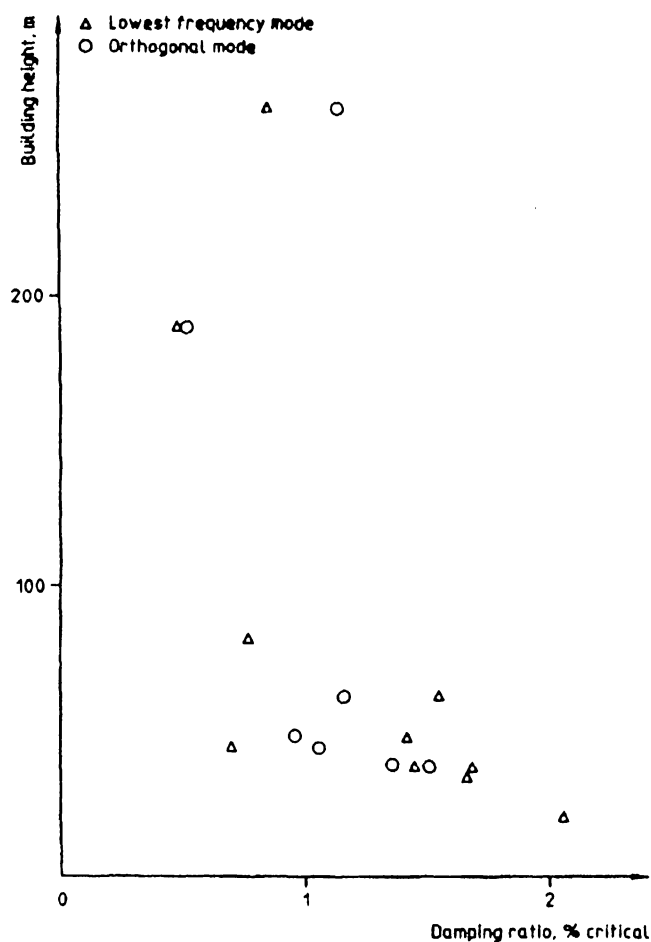


Figure D.2 — Building height versus damping ratio for the fundamental translation modes of 10 buildings where soil/structure interaction was negligible (from decay measurement)

D.4 Natural frequencies and damping values in low-rise buildings

The characteristics of 96 low-rise buildings are presented in references [37] and [38]. The buildings were located in the USA and are described as 1, 1½ and 2 storey buildings with basements, partial basements or crawl spaces. The data show that the average measured frequency decreases with building height.

Figure D.3 shows a histogram relating the number of buildings to their measured frequencies. It is important to note the range of frequencies which is encountered and thus the error involved in using an empirical prediction. There is no obvious tendency for the frequencies to vary with the age or location of the houses, and there is no correlation of the frequencies with plan dimensions.

Figure D.4 shows a histogram relating the number of buildings to their damping ratios. This indicates generally higher damping ratios than for taller buildings and shows the range of damping values which may be encountered. No obvious relationship between damping and building geometry exists.

D.5 Non-linear behaviour

The previous clauses discuss the natural frequency and the damping of each mode and this might give the impression that these quantities are invariant. However, they do vary with amplitude of motion and for earthquake analyses this might be important (albeit difficult to quantify). In general, wind loading induces small amplitude motion (in comparison with large earthquakes) and the changes in natural frequency and damping over the range of amplitudes normally encountered is small. In one building which was subjected to forces equivalent to a range of winds from light to hurricane force, changes of 3 % in frequency and 30 % in damping were recorded [36]. It can be appreciated that these changes are perhaps not significant and can be ignored for design purposes.

D.6 Final comment

The general conclusion which can be reached from this annex is that theoretical predictions are likely to involve considerable inaccuracies. Consequently, theoretical analyses should consider these possible inaccuracies by carrying out parametric variation and, for important structures, the design calculations should be verified using experimental measurements when the structure is complete.

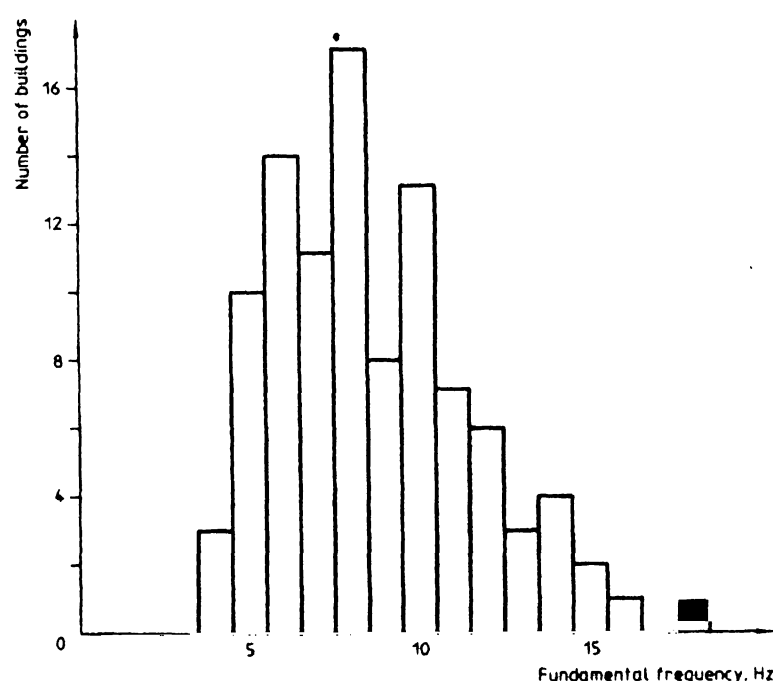


Figure D.3 — Frequencies measured in 96 low-rise buildings

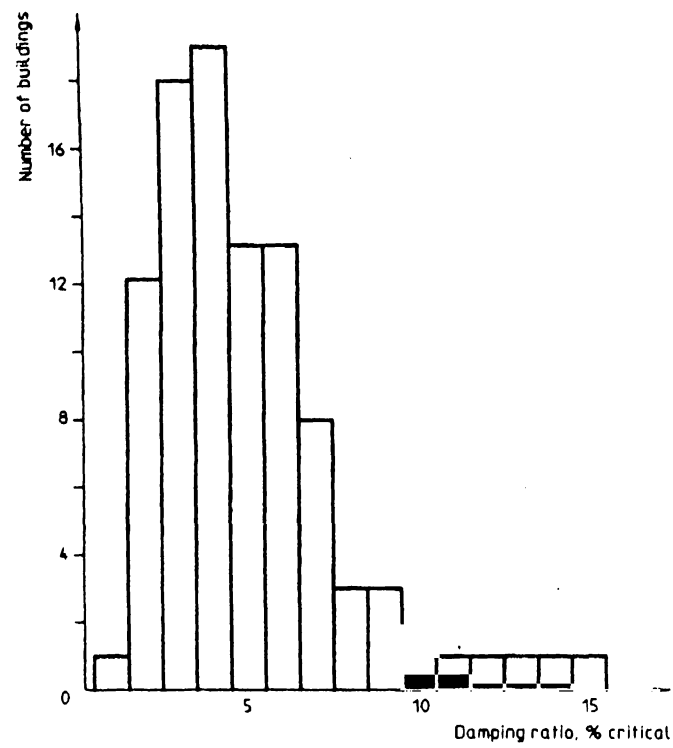


Figure D.4 — Damping ratios measured in 96 low-rise buildings

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Amendments Issued Since Publication

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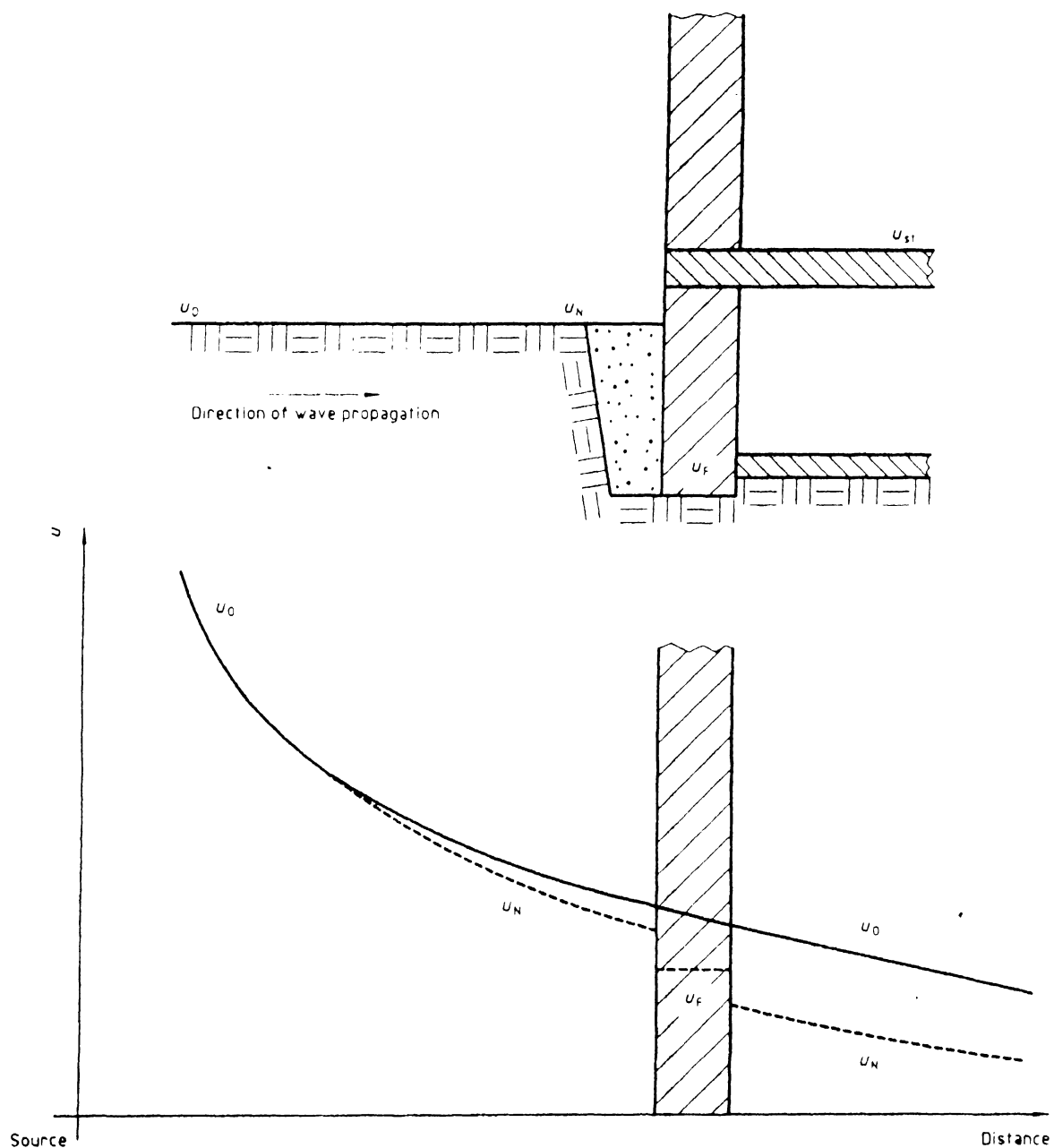
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Symbols:

u is the displacement, velocity or acceleration amplitude of the sinusoidal wave;

u_0 is the free-field amplitude;

u_N is the amplitude on the soil surface near an existing building;

u_F is the amplitude in the base of the foundation;

u_{st} is the amplitude at an arbitrary position in the structure.

$$r_0 = u_F/u_0$$

$$r_N = u_F/u_N$$

Figure E.1 — Notations, illustrated at a horizontally propagating wave

E.2 Theoretical considerations

Soil-structure interaction influences the dynamic response of all structures to some degree. Only a rigid building bonded to rigid ground would respond in the same way as the ground. In reality, the ground does not have an infinite rigidity and may provide a mechanism for the radiation and dissipation of energy. Hence it can be thought of as acting as a spring and dashpot system or a series of such systems just below the foundation.

The degree to which soil-structure interaction is a significant aspect of structural response depends on the dynamic parameters of the structure and of the ground, in particular on the natural frequencies of the structure and the shear stiffness of the ground. When considering relatively stiff low-rise buildings (low rise = 6 m to 7 m high), the problem may be examined as the vertical response of a rigid mass on a spring and a dashpot adjusted to match the analytical solution with the ground as semi-infinite isotropic and homogeneous elastic halfspace. Such simple concepts suggest that the maximum amplification to be expected in the vertical direction is not likely to exceed 2. Rocking and sliding modes can also be explored in a similar manner and suggest that somewhat higher magnifications can be theoretically achieved in most cases. However, vertical amplification is surely limited because energy captured by the structure from the passing wave is reradiated into the ground thus damping the amplitude response.

Full consideration of soil-structure interaction should take account of the layering of the soil, the variation of shear stiffness with depth, the effects of building load on soil stiffness, the effect of shear strains on soil stiffness, the geometry of the foundation, and foundation embedment, as well as the frequency content of the excitation.

Dynamic soil-structure interaction is one of the central problems in earthquake engineering, and over the last two decades methods of analysis have been highly developed, mainly for the nuclear industry, giving rise to a vast literature (see references [39] to [45]). Refined analysis has also been used for wind and man-made loading and some simplified rules have been derived (see references [46] and [47]).

These advanced analytical methods can be grouped into two classes:

- a) the direct method, whereby the soil and structure are treated together; the ground may be represented by finite elements, lumped parameters or both (hybrid models);
- b) the substructure method, whereby the response of the ground and structure are calculated as separate systems with a separation between ground and structure to which springs and dashpots or stiffness functions are applied.

Another approach is the response spectrum, widely used in earthquake engineering and other shock loading (see reference [48]). It can be adapted to take some account of soil-structure interaction by reducing the natural frequency assessed for a structure on soils of low stiffness. The effects of soil response can be allowed for, in part, by using design response spectra which vary according to the shear modulus depth profile of the soil.

Generally, the closer the frequency of the excitation is to the natural frequency of a building or building element the greater will be the response. Earthquakes, with low frequencies of 0,5 Hz to 8 Hz, will tend to excite the lower natural frequencies of buildings; man-made excitation is generally at higher frequencies and tends to excite the structural elements of a building. Furthermore, the range of vertical frequencies of building elements (6 Hz to 40 Hz) lies in the range of man-made excitation, leading to the relatively large bending responses which have been observed in ceilings (see reference [49]).

E.3 Relationship between vibration at the ground surface and at the foundation

There are difficulties associated with measurements on the ground near the building, for example:

- the measuring point is usually remote from the positions of interest within the structure;
- there are more uncertainties in coupling the transducer to the ground than in fixing it to a building part;
- the soil near a building is often disturbed;
- vibration amplitudes near a building may change with distance from the building as a proportion of the wavelength.

The direct methods for analysis of soil-structure interaction are expensive and need detailed knowledge of soil properties, however, they can give some guidance on the following factors influencing r_N .

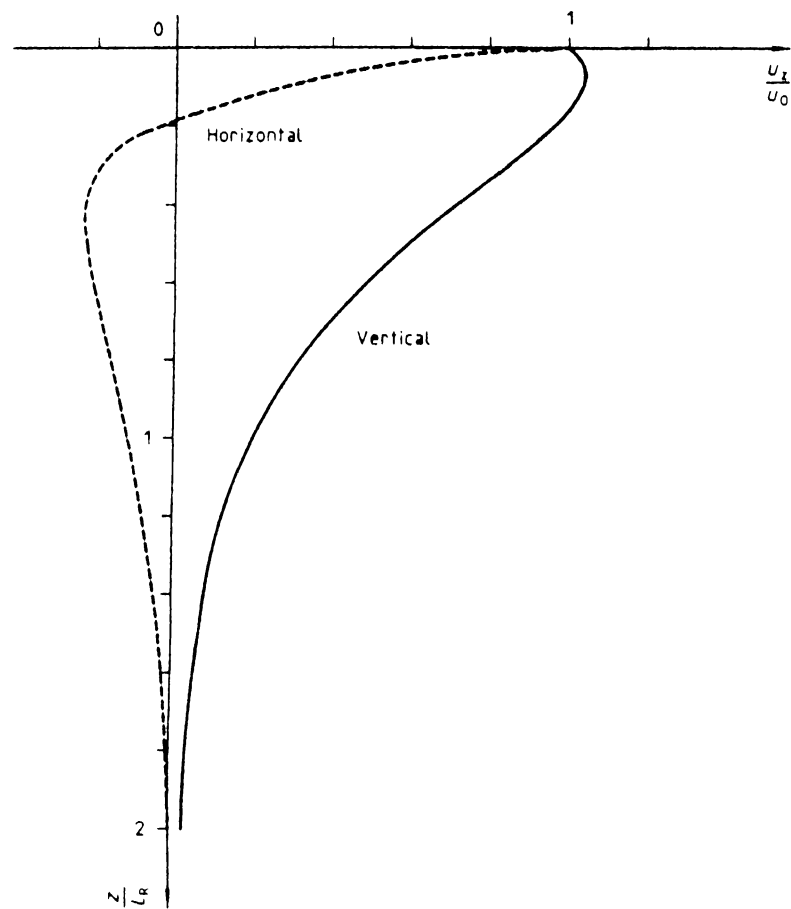
- a) The amplitude of vibration may be affected by reflection at the front of the foundation (with respect to the travelling wave) and decreased at the rear side by dissipation and front side reflection. These effects depend on the foundation size, depth and excitation wavelength.
- b) Where the propagation behaves like a surface Rayleigh wave (which is usual for distant sources), the amplitudes decrease with depth (see, for example, figure E.2), so deeper foundations pick up less motion.
- c) Strong earthquake motions are usually modelled as vertically propagating horizontally polarized shear waves with amplitudes increasing as the waves pass upwards from high rigidity. So again, deeper foundations may pick up smaller vibration.

Such complexities preclude a definitive set of rules relating r_N and r_0 to the category of structure and character of excitation, but both measurements (see reference [50]) and theoretical studies indicate that in most situations of man-made excitations the value of r_N is likely to be unity or less. This has been supported by results of a questionnaire¹⁾ which has indicated that for vertical motion without regard to frequency, r_N was in the range 0,3 to 0,6. The maximum magnification recorded was in the horizontal response and amounted to a 13 % increase. Histograms of the replies to the questionnaire are given in figures E.3 and E.4.

This general reduction of vertical vibration on the foundation as compared with that on the soil surface near a building may not hold in cases where there is a marked rocking response to continuous vibration.

As for preferred positions of measurement near a building, it is suggested that these positions should be less than 2 m or 1/10 of the dominant wavelength away from the building.

1) The questionnaire contained various ground conditions as well as various types of vibration excitation.



λ_R is the Rayleigh wavelength.

Figure E.2 — Variation of vibrational amplitude u_z with depth z of a Rayleigh wave

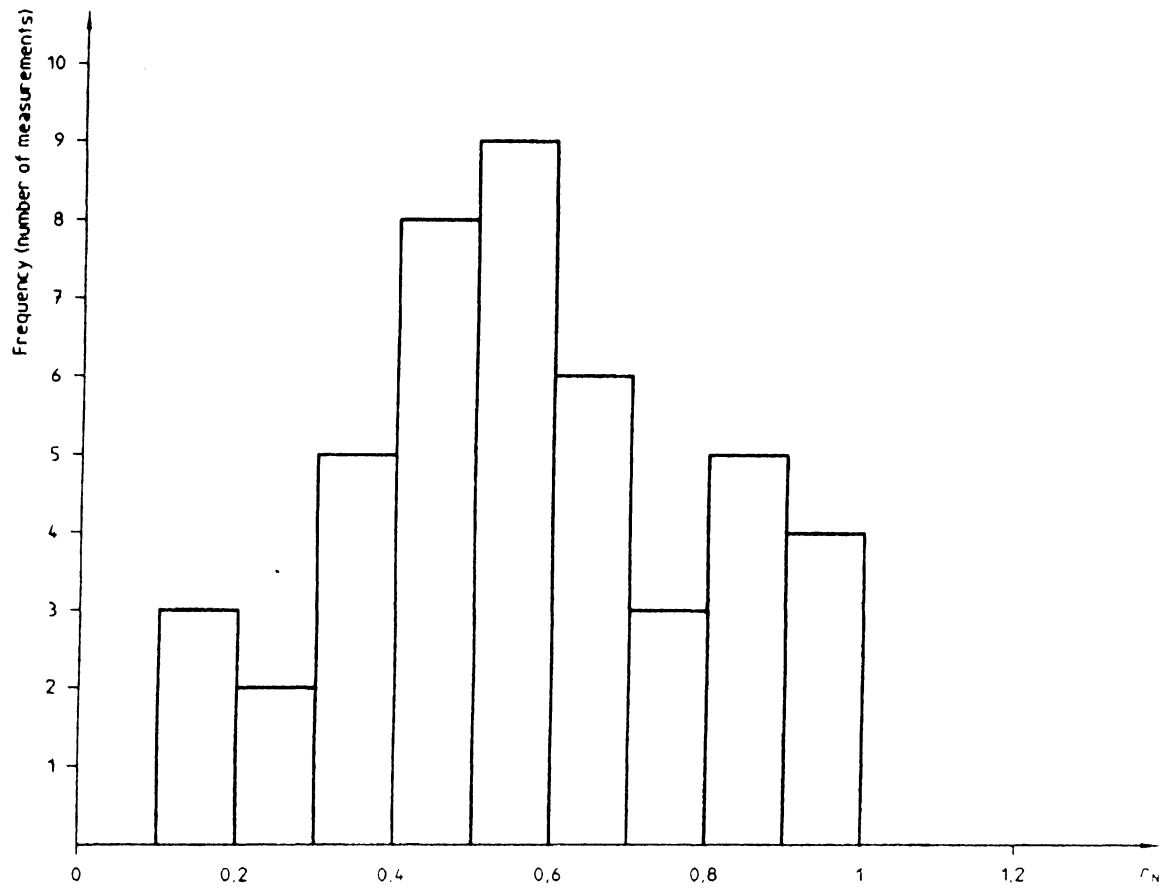


Figure E.3 — Frequency distribution of r_N (vertical direction of vibration)

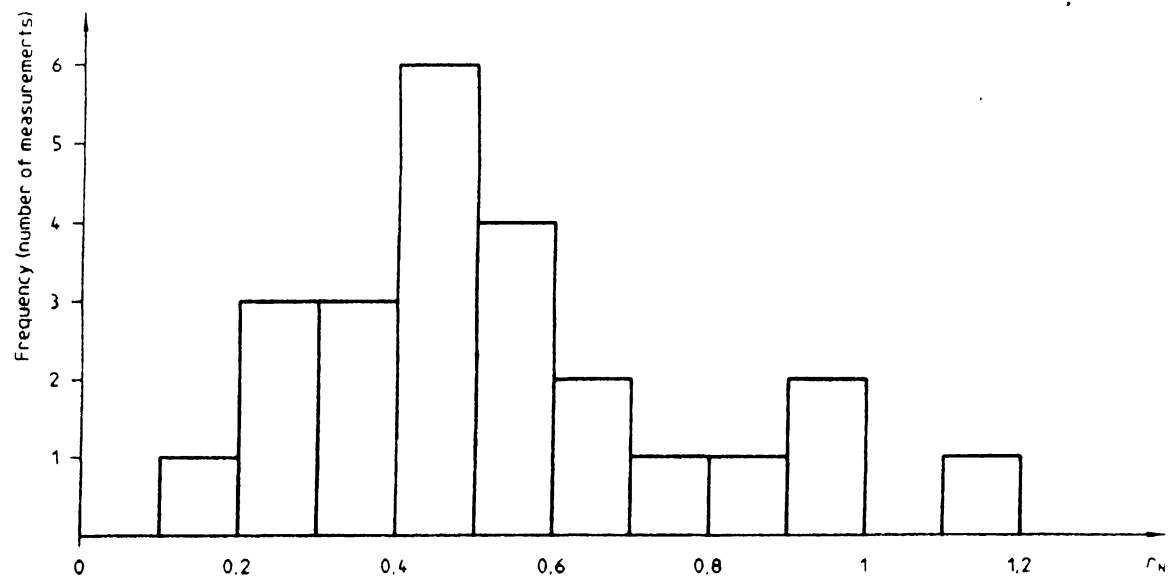


Figure E.4 — Frequency distribution of r_N (horizontal direction of vibration)

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Add references [39] to [50] to annex F.

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(MED 28)

Indian Standard

**MECHANICAL VIBRATION AND SHOCK —
VIBRATION OF BUILDINGS — GUIDELINES
FOR THE MEASUREMENT OF VIBRATIONS
AND EVALUATION OF THEIR EFFECTS
ON BUILDINGS**

1 Scope

This International Standard establishes the basic principles for carrying out vibration measurement and processing data, with regard to evaluating vibration effects on buildings. It does not cover the source of excitation except insofar as the source dictates dynamic range, frequency or other parameters. The evaluation of the effects of building vibration is primarily directed at structural response, and includes appropriate analytical methods where the frequency, duration and amplitude can be defined. This International Standard only deals with the measurement of structural vibration and excludes the measurement of airborne sound pressure and other pressure fluctuations although response to such excitations is taken into consideration.

A building, for the purposes of this International Standard, is defined as any above-ground structure, which man frequently inhabits. This excludes from consideration certain items of plant, for example columns, stacks, headframe, containments, even though they may receive intermittent visits from operating staff.

The structural response of buildings depends upon the excitation; to this end this International Standard examines the methods of measurements as affected by the source, i.e. frequency, duration, and amplitudes as induced by any source, such as earthquakes, explosions, wind effects, sonic booms, internal machinery, traffic, construction activities and others.

NOTE 1 There are differences between earthquakes and man-made vibrations which affect recording conditions. Earthquake-fault-rupture sources are large in size and much deeper than most man-made sources. They can cause damage at great distances, have much greater energy flux and duration and a different pattern of wave propagation. Consequently, for the same parameter value (for example peak particle velocity), the effects on buildings are different.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards

ISO 2041:1975, *Vibration and shock — Vocabulary*

ISO 2631-2:1989, *Evaluation of human exposure to whole-body vibration — Part 2: Continuous and shock-induced vibrations in buildings (1 to 80 Hz)*.

ISO 4356:1977, *Bases for the design of structures — Deformations of buildings at the serviceability limit states*

ISO 5348:1987, *Mechanical vibration and shock — Mechanical mounting of accelerometers*.

IEC 68-2-27:1987, *Environmental testing — Part 2: Tests — Test Ea and Guidance: Shock*.

3 Source-related factors to be considered

3.1 Characteristics of vibration responses in buildings

The types of vibration can be classified as

- a) deterministic,
- b) random,

and further subdivided as given in 8.2

For each type of vibration, a minimum amount of information is needed so that adequate definition of the type of vibration can be drawn up (see ISO 2041).^[1]

3.2 Duration

The duration of the dynamic exciting force is an important parameter. For the purposes of this International Standard, the response can be regarded as continuous or transient, and the type of response will be dictated by the relationship between the time constants associated with the structural response and the forcing function.

The time constant of a resonance response for resonance, r , in seconds, τ_r , is given by

$$\tau_r = \frac{1}{2\pi \xi_r f_r}$$

where

ξ_r represents the influence of the damping and depends on the kind of excitation (linear or non-linear);

f_r is the resonance frequency.

Two cases can thus be defined (without regard to whether or not the excitation is deterministic or random):

— Continuous

If the forcing function impinges on the structure continuously for more than $5\tau_r$, then the vibration is regarded as continuous.

— Transient

If the forcing function exists for a time which is less than $5\tau_r$, then the response is regarded as transient.

Since forcing functions which occur naturally are often not well behaved it may be that responses do not fall easily into a single category. For example blasting even with several intervals would be considered transient.

3.3 Frequency and range of vibration intensity

The frequency range of vibrations of interest depends upon the distribution of spectral content over the frequency range of the excitation and upon the mechanical response of the building. This pinpoints the spectral content as a most important property of vibration input. For simplicity's sake, this International Standard deals with frequencies ranging from 0,1 Hz to 500 Hz; it covers the response of buildings of a wide variety and building elements to excitation

from natural (wind and earthquake) and to man-made (construction, blasting, traffic) causes. Internal machinery may require higher frequencies to be recorded.

Most building damage from man-made sources occurs in the frequency range from 1 Hz to 150 Hz. Natural sources, such as earthquakes, usually contain energy at lower frequencies in the range from 0,1 Hz to 30 Hz at damaging intensities. Wind excitation tends to have significant energy in the frequency range from 0,1 Hz to 2 Hz.

Vibration levels of interest range from a few to several hundred millimetres per second depending on frequency.

4 Building-related factors to be considered

The reaction of buildings and building components to dynamic excitation depends upon response characteristics (for example natural frequencies, mode shapes and modal damping) as well as the spectral content of the excitation. Cumulative effects should be considered, especially at high response level and long exposure times where fatigue damage is a possibility.

4.1 Type and condition of buildings

In order to describe properly and categorize the visible effects of vibration and the results of instrumental measurements, a classification of buildings as defined in clause 1 is needed. For the purposes of this International Standard, a classification of buildings is set out in annex A.

4.2 Natural frequencies and damping

The fundamental natural frequencies of a building or of parts of the building influence its response and need to be known to allow the several methods of evaluating vibration to be applied. This may be achieved by spectral analysis of low-level response to ambient excitation or by the use of exciters.^[2]

Where a full response analysis is not undertaken and an assessment of potential vibration severity is needed, empirical expressions relating the height of a building to the fundamental period can be used.^{[3], [4], [5]}

Experimental studies^[6] have indicated the range of fundamental shear frequency of low-rise buildings 3 m to 12 m high to be from 4 Hz to 15 Hz. Damping behaviour is generally amplitude-dependent. The natural frequency and damping behaviour of stationary structures will be dealt with in a future addendum to this International Standard.

4.3 Building base dimensions

Ground-borne vibrations may have wavelengths of a few metres to several hundreds of metres. The response excitation from shorter wavelengths is complex and the foundations may act as a filter. Smaller domestic buildings would generally have base dimensions smaller than the characteristic wavelengths of all but the highest-frequency sources (for example precision blasting in rock).

4.4 Influence of soil

It is now common in earthquake engineering studies to take into account the influence of the soil. [3]

An evaluation of such interaction effects is sometimes justified for man-made vibrations; such an evaluation demands that the shear wave velocity or dynamic rigidity modulus in an appropriate volume of ground material be determined. Empirical, numerical and analytical procedures may be obtained from several sources. [7]

Foundations on poor soils and fill may suffer from settlement or loss of bearing capacity due to ground vibration. The risk of such effects is a function of the particle size of the soil, its uniformity, compaction¹⁾, degree of saturation, internal stress state, as well as the peak multiaxial acceleration and duration of the ground vibration. Loose, cohesionless, saturated sands are especially vulnerable and in extreme circumstances may undergo liquefaction. This phenomenon needs to be taken into consideration in evaluating vibrations and explaining their effects [8],[9] (See also annex A)

5 Quantity to be measured

The characterization of both the nature of vibration input and the response may be effected by a variety of displacement, velocity or acceleration transducers. These can furnish a record as a function of time. It is the usual practice to sense a kinematic quantity, such as velocity or acceleration. From knowledge of the appropriate transfer function of the sensing system, each quantity can be derived from another by integration or differentiation. Integration at lower frequencies calls for care and confidence in amplitude-phase response of the transducer and instrument chain (see clause 6). As long as the requirement on data collection, treatment and presentation (see clause 6) can be met, the sensor may respond to any chosen quantity. Experience suggests that there are preferred measuring quantities for different situations (see table 1).

1) Soil compaction may be monitored by precise levelling.

6 Measuring Instrumentation

6.1 General requirements

Vibration is measured with a view to using the data in some evaluatory or diagnostic procedure or to monitoring a vibration with some established target level in mind. For evaluation, the minimum performance shall be sufficient to meet the requirements laid down in clause 3 and clause 7 with regard to the evaluatory procedures described in clause 9.

It is not expected that a single instrumentation system would meet all the requirements of frequency and dynamic range for the wide range of structures and inputs for which this International Standard is applicable.

The measuring system includes the following instrumentation:

- transducers (see 6.2);
- signal-conditioning equipment;
- data recording system.

The frequency response characteristics (amplitude and phase) need to be specified for the complete measuring system when connected together in the manner to be used.

The degree to which measured motion needs to approach true motion will depend upon the character of the investigation and the evaluation method used.

The minimum requirement for 9.2.2 and 9.2.3 is that the vibration shall be characterized by a continuous measurement of the peak particle velocity values.

The minimum requirement for 9.2.4 is that the time history of the vibration shall be recorded over sufficient duration and with sufficient accuracy to establish its spectral characteristics. Analog or digital methods are available subject to the stipulations laid down in this clause.

6.2 Choice of transducers

The choice of transducers is important for the correct evaluation of vibratory motion. In general, transducers may be divided into two groups producing a linear output either above or below the natural resonance of the sensing mechanism. The so-called "velocity pick-up" or "geophone" widely used in structural vibration measurement is typical of an electromagnetic sensor operating at a frequency above its natural resonance; whereas a piezo-electric accelerometer usually operates below

Table 1 — Typical range of structural response for various sources

Vibration forcing function	Frequency range Hz	Amplitude range μm	Particle velocity range mm/s	Particle acceleration range m/s^2	Time characteristic	Measuring quantities
Traffic road, rail, ground-borne	1 to 80	1 to 200	0,2 to 50	0,02 to 1	C/T	pvth
Blasting vibration ground-borne	1 to 300	100 to 2 500	0,2 to 500	0,02 to 50	T	pvth
Pile driving ground-borne	1 to 100	10 to 50	0,2 to 50	0,02 to 2	T	pvth
Machinery outside ground-borne	1 to 300	10 to 1 000	0,2 to 50	0,02 to 1	C/T	pvth/ath
Acoustic traffic, machinery outside	10 to 250	1 to 1 100	0,2 to 30	0,02 to 1	C	pvth/ath
Air over pressure	1 to 40				T	pvth
Machinery inside	1 to 1 000	1 to 100	0,2 to 30	0,02 to 1	C/T	pvth/ath
Human activities a) impact b) direct	0,1 to 100 0,1 to 12	100 to 500 100 to 5 000	0,2 to 20 0,2 to 5	0,02 to 5 0,02 to 0,2	T	pvth/ath
Earthquakes	0,1 to 30	10 to 10^5	0,2 to 400	0,02 to 20	T	pvth/ath
Wind	0,1 to 10	10 to 10^5			T	ath
Acoustic inside	5 to 500					
Key C — continuous } (simplified categories, see 3.1 and 3.2) T — transient } pvth — particle velocity time history ath — acceleration time history NOTES 1 The ranges quoted are extremes but indicate the values which may be experienced and which may have to be measured (see also note 3). Extreme ranges of amplitude of displacement and frequency have not been used to derive particle velocity and acceleration. 2 The frequency range quoted refers to the response of buildings and building elements to the particular type of excitation. It is indicative only. 3 Vibration values within the ranges given may cause concern. There are no standards which cover all varieties of building, condition and duration of exposure, but many national codes associate the threshold of visible effects with peak particle velocities at the foundation of a building of more than a few millimetres per second. A significant probability of some damage is linked to peak particle velocities of several hundred millimetres per second. Vibration levels below the threshold of human perception (see ISO 2631-2) may be of concern in delicate and industrial processes.						

the resonance. There are electromagnetic sensors which operate below their natural frequency, such as are widely used strong-motion seismographs.

In practice, care should be exercised in using the phase information from the "velocity pick-up" type of transducer at the lower frequencies. If both am-

plitude and phase response are critical, linear performance of the whole measuring chain should be ensured. A low-frequency cut-off ten times the lowest required measured frequency is often recommended as a good compromise and, in general, the measured signal should be 5 dB above the background noise.

Velocity pick-ups generate a relatively high signal thus simplifying the instrument chain. If particle velocity is needed, the piezo-electric accelerometer output needs integrating, and with transients the response of the whole chain should be verified.

6.3 Signal-to-noise ratio

The signal-to-noise ratio should generally be not less than 5 dB. If the signal-to-noise ratio is between 10 dB and 5 dB, the measured value should be corrected (i.e. diminished) and the correction method reported. Background noise is defined as the sum of all the signals not due to the phenomenon under investigation.

7 Position and fixing of transducers

7.1 Positions

7.1.1 General

The proper characterization of the vibration of a building requires a number of positions of measurement which depend upon the size and complexity of the building.

Where the purpose is to monitor with regard to imposed vibration, the preferred position is at the foundation, a typical location being at a point low on the main load-bearing external wall at ground floor level when measurements on the foundations proper are not possible.

Measurements of vibration response generated by traffic, pile-driving and blasting, especially at a great distance, show that the vibration may be amplified within the building and in proportion to the height of the building. It may, therefore, be necessary to carry out simultaneous measurements at several points within the building. Simultaneous measurements on the foundation and the ground outside will serve to establish a transfer function.

Where a building is higher than 4 floors (≈ 12 m), subsequent measuring points should be added every 4 floors and at the highest floor of the building.

Where a building is more than 10 m long, measuring positions should be installed at horizontal intervals of approximately 10 m.

Additional measuring points may have to be made in response to requests by occupants and as a consequence of initial observations.

For investigations of the analytical type, positioning will depend upon the modes of deformation to be considered. Most practical cases are economically limited to identification of fundamental modes and

measurement of maximum responses in the whole structure together with observations on elements such as floors, walls and windows.

7.1.2 Measurement in a building

Transducer placement in a building depends on the vibration response of concern. As described in 7.1.1, assessment of the vibration being input to a building from ground-borne sources is best done by measurements on or near the foundation. Determination of structural racking or of shear deformation of the building as a whole requires measurements directly on the load-bearing members which afford the structures' stiffness. This usually means three components of measurement in corners, although other arrangements are possible.

Sometimes, floor or wall motions are of concern, with maximum amplitudes at mid-span locations. Although sometimes very severe, these vibrations are usually unrelated to structural integrity. [11]

Investigations associated with sources within a building usually involve a trial-and-error exploratory phase.

In cases where measurements related to equipment are to be made, such as when monitoring computers, relays and other installations sensitive to vibration, the measurement should reflect the incoming vibration. The point of measurement should be placed on or at the foundation or on the frame of the equipment. In this case, the equipment should if possible be switched off for the measurement.

In cases where measurements related to ground-transmitted vibration are to be made, such as where ground vibration sources are being studied, it is usual to orientate the sensors with respect to radial direction defined as the line joining the source and the sensor. When studying structural response to ground vibration, it is more realistic to orientate with respect to the major and minor axes of the structure. It is often not possible to make measurements at the foundation proper so instruments have to be coupled to the ground.

Vibration measurements made on or below the ground surface may be affected by the variation of the amplitude of a surface wave with the depth. Building foundations may then be exposed to a motion which is different from the one observed on the ground surface depending on the wavelength, foundation depths and geotechnical conditions.

For wind-induced vibration, vertical components are often dispensed with and test instrument disposition should be made with rotational and translational modes in mind.

7.2 Fixing of transducers

7.2.1 Coupling to structural elements

The mounting of vibration transducers to vibrating elements or substrate should comply with ISO 5348 with regard to accelerometers. The aim should be to reproduce faithfully the motion of the element or substrate without introducing additional response. Care should be taken with triaxial assemblies to avoid rocking or bending.

The mass of the transducer and monitoring unit (if any) shall not be greater than 10 % of the building element to which it is fixed. Mounting shall be as stiff and as light as possible.

Brackets should be avoided. It is better to fix three uniaxial transducers to three faces of a metal cube rigidly mounted by means of studs or quick-setting, high modulus resin. The transducer mounting can be secured to the frame of the building by expansion bolts. Gypsum joints are preferred when measuring on lightweight concrete elements.

In special circumstances, it is acceptable to glue the transducer or attach it using magnetic attraction. For measurements indoors on horizontal surfaces, double-sided adhesive tape may be used on all hard surfaces for accelerations below 1 m/s^2 , although mechanical fixings are preferred.

Measurements on floors having compliant coverings tend to give distorted results and should be avoided. Where it is not possible to relocate the transducers, comparative measurements with different mass and coupling conditions for the mounting block should be made to evaluate the effect of the compliant coverings.

7.2.2 Coupling to the ground

Soil conditions permitting, the transducer may be fixed to a stiff steel rod (having a diameter of not less than 10 mm), driven through a loose surface layer. This rod should not project more than a few millimetres above ground surface. Care should be taken to ensure close contact between the transducer and the ground. In cases where acceleration greater than 2 m/s^2 is expected, a firm ground mounting is needed to prevent slippage. Where transducers have to be mounted in the ground in order to minimize coupling distortion, they should be buried.

Where transducers have to be mounted in the ground, in order to minimize coupling distortion, they should be buried to a depth at least three times the main dimension of the transducer/mounting unit. Alternatively, they can be fixed to a rigid surface plate with a mass ratio ($m/\rho r^3$) not more than 2,

where m is the mass of the transducer and plate and r is the equivalent radius of the plate. The rigid surface plate may, for example, be a well-bedded paving slab. For most soils, the mass density, ρ , ranges from $1\,500 \text{ kg/m}^3$ to $2\,600 \text{ kg/m}^3$.

8 Data collection, reduction and analysis

8.1 General

The aim of measurement is to acquire sufficient information to enable the selected method of evaluation (see clause 9) to be carried out with a sufficient degree of confidence.

The amount of information required to characterize vibration properly increases as the complexity of the vibration increases from simple periodic to non-stationary random and transient motion.

Data collection systems which are adequate for defining a periodic motion over a specified frequency range may not be adequate for establishing even a single parameter index (for example peak particle velocity) for a more complex motion.

8.2 Description of data

Any data resulting from the observation of a physical process can broadly be described as deterministic or random. Deterministic data are those that can be described by an explicit mathematical function.

Figure 1 illustrates categories of the types of data that may be encountered. A description of each category is given in ISO 2041.

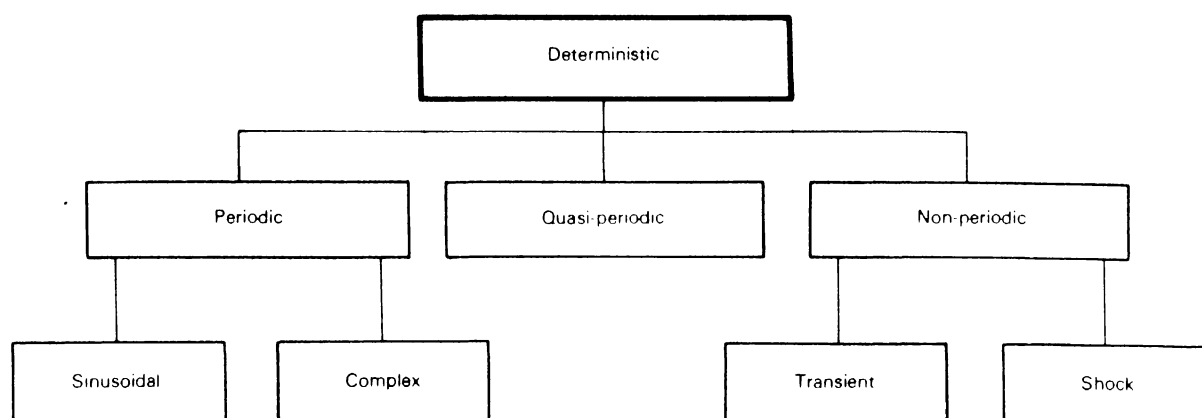
8.3 Data analysis procedures

Having decided into which of the main categories illustrated in figure 1 the data fall, the type of analysis will normally be apparent. If the data is categorized as deterministic, then a simple analysis (r.m.s., peak-to-peak, mean square) will often suffice.

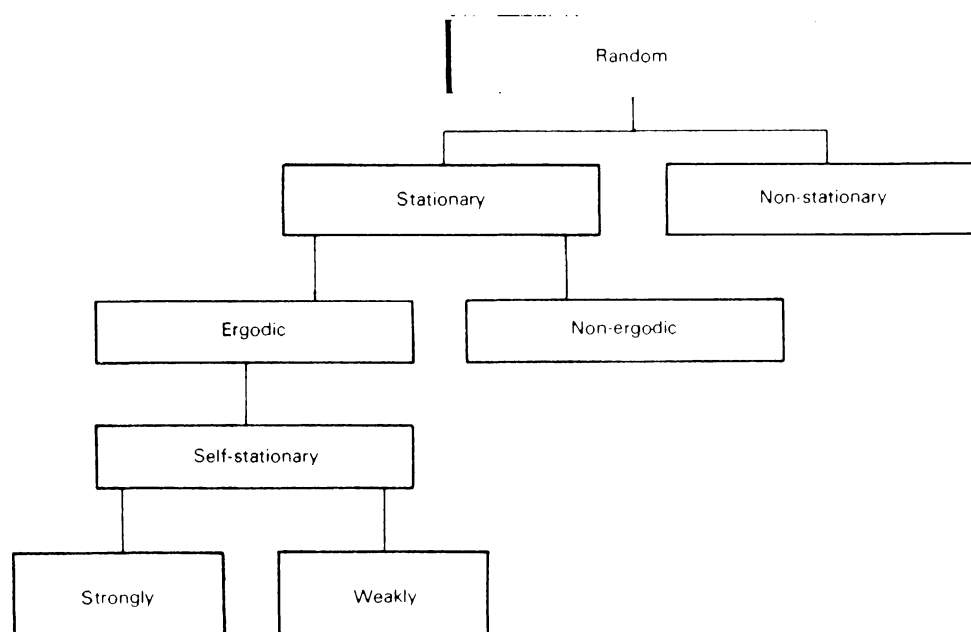
If the special case of non-periodic deterministic data, peak amplitude should be determined without preconditioning (although a d.c. component may be compensated by analysis of a section of the record prior to capture of the signal). Details are given in [10] and [12]. A dynamic range of 40 dB is adequate for most purposes, but 50 dB is preferred.

Random data should be tested for stationarity (see [13]).

If the data are deemed to be stationary, the procedures outlined in annex C are appropriate and are described in more detail in [10], [12], [13] and [14].



a) Deterministic data



b) Random data

Figure 1 — Categories of the types of data

9 Method of data evaluation

9.1 General

Evaluation of measurements should reflect both the purpose of those measurements and the type of investigation.

A full response analysis for predictive purposes requires information on structural details and conditions not usually readily obtainable. An investigator may, therefore, need to have an appropriate method of assessing the severity of vibration of a structure or a component with regard to the probability of damage. In such an assessment, the following factors need to be taken into account:

- a) resonant frequencies of basic structure and component parts (walls, floors, windows);
- b) damping characteristics of basic structure and component parts;
- c) type of construction, its condition and material properties;
- d) spectral structural features;
- e) characteristics of excitation;
- f) deflected form;
- g) non-linearity in amplitude response.

Although this International Standard is primarily concerned with the measurement and evaluation of the response, the chain of action, source, transmission path and transfer-function have to be borne in mind when evaluation is being made.

9.2 Types of investigation

For many of the parameters of interest, listed in 9.1 a) to g), the choice of instrumentation, its location within the building, the type of recording device and the number of data channels or measurement points desired, the duration of monitoring for the phenomena and the speed of data collection will immediately be decided. The outlining of instrumentation requirements in clause 6 and annex C has been arranged in such a way as to facilitate the selection of instrumentation to meet particular requirements. Beyond this it is important to delineate the degree of sophistication to be applied to the investigation. Instruments which characterize the vibration environment by a single quantity, such as those used in connection with human response and machine condition, may be used in a preliminary survey so long as the limited frequency responses are taken into account. For the purposes of this International Standard, a preliminary assessment, a monitoring pro-

gram, a field survey and a detailed engineering analysis are under consideration.

9.2.1 Preliminary assessment

Situations may arise where an assessment has to be made of vibration problems by desk study alone, usually before field measurements. Empirical methods can be used to estimate response provided that data on the source parameters and building response characteristics, such as fundamental frequency and damping, are available.

9.2.2 Exploratory monitoring

Very limited measurement of vibration on a building or over an area can indicate the existence of a problem requiring further investigation. High errors are not uncommon and this fact has to be kept in mind. (See also final paragraph in 9.2.3)

9.2.3 Field survey

A field survey would consist of a limited number (see also 7.1) of vibration measurement locations in order to assess the vibration severity often in comparison with values stipulated in codes or regulations.

In the case of vibrations which can be reproduced for a sufficient time, the same transducers can be used for the different points keeping a reference point at the foundation level near source.

As regards exploratory monitoring (see 9.2.2) and field surveys, measurements should be of an accuracy compatible with the uncertainties implicit in the vibration indices and empirical relationship used. Single parameter indices, such as peak particle velocity or peak acceleration and r.m.s. values, need, generally, only to be known to within $\pm 10\%$ at the 68 % confidence level.

9.2.4 Engineering analysis

When complex structures of vital importance are being subjected to vibration excitation of a magnitude that requires serious consideration of the consequences, the structural behaviour needs to be assessed in a more detailed way.

Instrumentation for monitoring the time history should be mounted at a number of locations to ensure that specific values for that structure are not exceeded.

If the ground-to-foundation transfer function is of concern, simultaneous recording outside and on the foundation should be carried out. The recording position on the foundation is at a point on the main wall at ground floor level or the basement.

The number of measuring points and their location have to be defined and modified according to the characteristics of the building and the observations noticed during monitoring.

The natural frequencies of buildings should be determined, if possible.

In the case of vibrations which can be reproduced for a sufficient time, the same transducers can be used for the different points keeping a reference point at the foundation level near the source.

For structures of vital importance, response analysis should be carried out as well as an estimate of structure loading. A full engineering analysis requires a system which would enable frequency to be estimated to $\pm 1\%$ and damping to $\pm 10\%$.

9.3 Reporting of control activities

The style of reporting should be consistent with the type of investigation (see 9.2), but as a minimum the report should include the following:

- a) Risk analysis
 - 1) Description of the source
 - 2) Type and condition of building, in accordance with annex A.
 - 3) Purpose of the measurement.
 - 4) Reference to the standard being used and type of investigation
- b) Measurements
 - 1) Position of transducer and manner of coupling
 - 2) Type and make of transducer, signal conditioning and recording equipment
 - 3) Calibration factors for the instrumentation system
 - 4) Frequency range and linearity
 - 5) Assessment of the sources of error.
 - 6) — For monitoring or survey investigation (see 9.2.2 and 9.2.3), it is sufficient to make continuous registrations of peak particle velocity values.
— For further investigation (see 9.2.4), a permanent record of time history should be made available.
- c) Building inspection

- 1) Inspection of buildings before vibration exposure, with graphical reporting of cracks and other damage.
 - 2) Inspection of the same buildings after the vibration exposure.
 - 3) Evaluation of observed damage
- d) Reference to other relevant International Standards.

9.4 Evaluation for prediction

An existing building may be exposed to a new source, external or internal, and some assessment of the expected vibration response is needed. Given sufficient information about the characteristics of the input and the properties of the structure, numerical analyses using one or other well known techniques of response spectra, Fourier response, time step integration^[15] may be used for important buildings. Alternatively, a characteristic index, such as a kinematic quantity (displacement, velocity, acceleration) (see 9.6), can be related to expected performance using empirical data appropriate to the type of building.^[7]

A convenient way of expressing a vibration in the frequency domain is the "response spectrum", widely used in engineering.^[7] (See IEC 68-2-27) For the special case of zero damping, it is close to the Fourier amplitude spectrum.

In most cases, the response characteristics of the structure are ill defined although dynamic test procedures are now available.^[7]

9.5 Evaluation for vibration study in existing buildings

The evaluation of vibration status in existing buildings may be carried out at different levels of sophistication consistent with the investigative procedures outlined in 9.2. Indications of vibration severity may be in terms of stresses or kinematic quantities. In some cases, the direct observation of crack opening or extension affords valuable information on the response and may indicate progressive deterioration.^{[15], [16]}

9.6 Kinematic quantities as indices of vibration severity in structures

For several decades studies have been carried out to relate the vibration severity in terms of a quantity such as peak displacement, velocity, acceleration, related to visible effects on structures.

Where measurements are made upon a component, a kinematic quantity, such as peak velocity, can be

expressed as a stress (see annex B) and, in turn, related in structural terms to allowable stress. When the kinematic quantity refers to whole-body structural response measured at some chosen position, the response frequency and damping of the structure, and duration of the input affect vibration severity. The kinematic quantity is then an empirical index and shall be qualified by the kind of building to which it refers (see 3.3).

Some account of these factors is embodied in the use of the peak spectral acceleration or velocity as a damage index^{[6], [11]} applicable to low-rise (one to three storeys high) and "whole" building response.^[16]

The dependence of severity rating on response frequency of both building and frequency content of the excitation is also recognized in the empirical correlations which strictly apply to buildings with a limited range of fundamental frequency in shear, and identify different severity ratings in different frequency bands. A broad guide to vibration levels of interest is given in table 1.

9.7 Probabilistic aspects

There is increasing evidence that the criteria relating vibration to visible effects on buildings (cosmetic, minor and major damage) should be approached in a probabilistic way.

For possible combinations of age and condition of a building, it may not be possible to establish an economic absolute lower limit.

This is particularly the case where either a peak kinematic value (usually particle velocity) of ground motion within a specified frequency band or a peak spectral velocity response spectrum acceleration or displacement is being used as an index of damage potential. Minimal risk for a named effect is usually taken as a 95 % probability of no effect.

The evaluation of the response of a building or component part may be assisted by measurements

of local strain or relative displacement (for example crack monitoring), although this would not constitute a measure of vibration status. It may, however, permit (with difficulty) a direct evaluation of composed dynamic stress for comparison with design criteria.

9.8 Fatigue factors

Repeated stress reversal over many cycles carries a risk of increasing fatigue failure. Reference for steel members can be made to appropriate design codes. Such guidance is not available for concrete, masonry and other building materials. Reference would have to be made to research. Long-term, low-level vibration amounting to 10^{10} load reversals may have to be taken into account for special structures, monuments, etc.^[17]

9.9 Description of damage

For the purposes of this International Standard, the damage is classified into the following categories:

— Cosmetic

The formation of hairline cracks²⁾ [21] on drywall surfaces, or the growth of existing cracks in plaster or drywall surfaces; in addition, the formation of hairline cracks in mortar joints of brick/concrete block construction.

— Minor

The formation of large cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.

— Major

Damage to structural elements of the building, cracks in support columns, loosening of joints, spalling of masonry cracks, etc.

NOTE 2 The description of damage has its equivalent in the intensity scales used by seismologists.

2) See ISO 4358.

Annex A (informative)

Classification of buildings

A.1 General

This annex provides simplified and helpful guidelines for classifying buildings according to their probable reaction to mechanical vibrations transmitted by the ground.

A dynamic system, for the purposes of this classification, consists of the **soil and strata**, in which are set the **foundations** (if existing), together with the **building structure** itself.

Table A.2 gives 14 simplified classes taking into consideration the following factors:

- type of construction (as ascertained from table A.1);
- foundation (see clause A.5);
- soil (see clause A.6);
- political importance factor

The frequency range is taken from 1 Hz to 150 Hz (see also 3.3), which covers most events met in industrial practice, blasting, piling and traffic. Shock directly introduced into the structure by industrial machinery is not included though its effects at some distance are. Shock produced by blasting, piling and other sources outside the strict confines of the structure are not included but the effects on the structure are. The buildings referred to exclude very tall structures with more than 10 storeys.

A.2 Structures Involved

A.2.1 The following structures are included in the classification.

- all buildings used for living and working (houses, offices, hospitals, schools, prisons, factories, etc.);
- publicly used buildings (town halls, churches, temples, mosques, heavier industrial mill-type buildings, etc.);

- elderly, old and ancient buildings of architectural, archeological and historical value;
- lighter industrial structures, often designed to the codes of building practice.

A.2.2 The following structures are not included in the classification:

- heavier structures such as nuclear reactors and their adjuncts and other heavy power plants, rolling mills, heavier chemical engineering structures, all types of dams, and containing structures for fluids and granular materials, for example water towers and tanks, petroleum storage, grain and other silos, etc.;
- all underground structures;
- all marine structures.

A.3 Definition of classes (see table A.2)

The classes are defined by taking as a reference a well maintained building in good repair. The reference building shall not have any constructional defects nor shall it have sustained accidental damage from earthquakes. If the construction does not fulfil these requirements, it shall be allocated to a lower class.

The order in which the structural types are classified depends on their resistance to vibrations, and also on the tolerances that can be accepted for the vibrational effects on structures, given their architectural, archeological and historical value.

Three important elements enter into the reaction of a structure under the effects of mechanical vibrations. The three elements are as follows:

- the category of the structure — table A.1 gives a preliminary classification of the categories of structures based on the groups defined in clause A.4 ;
- the foundation (see clause A.5);
- the nature of the soil (see clause A.6).

A.4 Categories of structures

A.4.1 Group 1 — Ancient and elderly buildings or traditionally built structures

The types of buildings considered in this group can be divided into the two following sub-groups:

- a) elderly, old or ancient buildings;
- b) all modern buildings constructed in older, traditional style using traditional kinds of materials, methods and workmanship.

This group, generally, is of heavier construction and has a very high damping coefficient, for instance due to soft mortar or plaster. This group also includes traditionally resilient structures in earthquake zones. Buildings in this group seldom have more than six storeys.

A.4.2 Group 2 — Modern buildings and structures

The types of buildings considered in this group are all of modern structure using relatively hard materials tied together in all directions, usually light in weight overall, and with little damping coefficient.

This group includes frame buildings as well as calculated load-bearing wall kinds. Buildings vary from being single- to multi-storey. All types of cladding are included. This group also includes some older types of buildings which are constructed using modern materials, tying and damping.

A.5 Categories of foundations

A.5.1 Class A

Class A includes the following types of foundation:

- linked reinforced concrete and steel piles;

- stiff reinforced concrete raft;
- linked timber piles;
- gravity retaining wall.

A.5.2 Class B

Class B includes the following types of foundation:

- non-tied reinforced concrete piles³⁾;
- spread wall footing;
- timber piles and rafts.

A.5.3 Class C

Class C includes the following types of foundation:

- light retaining walls;
- large stone footing;
- no foundations — walls directly built on soil.

A.6 Types of soil

Soils are classified into the following types:

Type a: unfissured rocks or fairly solid rocks, slightly fissured or cemented sands;

Type b: compact, horizontal bedded soils;

Type c: poorly compacted, horizontal bedded soils;

Type d: sloping surfaces with potential slip planes;

Type e: open granular, sands, gravels (non-cohesive), and cohesive saturated clays;

Type f: fill.

3) Piles, structurally connected, usually at level of pile caps.

Table A.1 — Categorization of structures according to group of building

Category of structure		Group of building (see clause A.4)	
		1	2
← Resistance to vibration decreasing	1	Heavy industrial multi-storey buildings, five to seven storeys high, including earthquake-resistant forms Heavy structures, including bridges, fortresses, ramparts	Two- and three-storey industrial, heavy-frame buildings of reinforced concrete or structural steel, clad with sheeting and/or infilling panels of blockwork, brickwork, or precast units, and with steel, pre-cast or <i>in situ</i> concrete floors Composite, structural steel and reinforced concrete heavy industrial buildings
	2	Timber frame, heavy, public buildings, including earthquake-resistant forms	Five- to nine-storey (and more) blocks of flats, offices, hospitals, light-frame industrial buildings of reinforced concrete or structural steel, with infilling panels of blockwork, brickwork, or precast units, not designed to resist earthquakes
	3	Timber-frame, single- and two-storey houses and buildings of associated uses, with infilling and/or cladding, including "log cabin" kinds, including earthquake-resistant forms	Single-storey moderately lightweight, open-type industrial buildings, braced by internal cross walls, of steel or aluminium or timber, or concrete-frame, with light, sheet-cladding, and light panel-infilling, including earthquake-resistant types
	4	Fairly heavy multi-storey buildings, used for medium warehousing or as living accommodation varying from five to seven storeys or more	Two-storey, domestic houses and buildings of associated uses, constructed of reinforced blockwork, brickwork or precast units, and with reinforced floor and roof construction, or wholly of reinforced concrete or similar, all of earthquake-resistant types
	5	Four- to six-storey houses, and buildings of associated urban uses, made with blockwork or brickwork, load-bearing walls of heavier construction, including "stately homes" and small palace-style buildings	Four- to ten-storey domestic and similar buildings, constructed mainly of lightweight load-bearing blockwork and brickwork, calculated or uncalculated, braced mostly by internal walls of similar material, and by reinforced concrete, preformed or <i>in situ</i> floors at least on every other storey.
	6	Two-storey houses and buildings of associated uses, made of blockwork, brickwork or pis-à-terre, with timber floors and roof Stone- or brick-built towers, including earthquake-resistant forms	Two-storey domestic houses and buildings of associated uses, including offices, constructed with walls of blockwork, brickwork, precast units, and with timber or precast or <i>in situ</i> floors and roof structures
	7	Lofty church, hall and similar stone- or brick-built, arched or "articulated" type structures, with or without vaulting, including arched smaller churches and similar buildings Low heavily constructed "open" (i.e. non-cross-braced) frame church and barn type buildings including stables, garages, low industrial buildings, town halls, temples, mosques, and similar buildings with fairly heavy timber roofs and floors	Single- and two-storey houses and buildings of associated uses, made of lighter construction, using lightweight materials, pre-fabricated or <i>in situ</i> , separately or mixed
	8	Ruins and near-ruins and other buildings, all in a delicate state All class 7 constructions of historical importance	

Table A.2 — Classification of buildings according to their resistance to vibration and the tolerance that can be accepted for vibrational effects

Class of building ¹⁾		Category of structure (see table A.1)							
		1	2	3	4	5	6	7	8
		Categories of foundations (capital letters) and types of soil (lower case letter) (see clause A.5 and clause A.6)							
↓ Level of acceptable vibration decreasing ↓	1	A a							
	2	A b	A a	A a	A a				
	3		A b B a	A b B a	A b	A a A b			
	4		A c B b	B b	A c	A c B a B b			
	5		B c	A c		B c	B a		
	6		A f		A d	B d	B b C a	B a	
	7			A f	A e	B e	B c C b	B b C a	
	8						B e C c	B c C b	
	9		B f				C d	B d C c	A a
	10			B f			C e	B e C d	A b
	11				C f	C f		C e	B a
	12						C f		B c C a
	13							C f	B d C b C c
	14								C d C e C f

1) High class number = high degree of protection required.

Annex B (informative)

Estimation of peak stress from peak particle velocity

The stresses in beams or plates vibrating close to resonance can be calculated from measurement of velocity or displacement and frequency, if the measurement is performed at the points of maximum vibrating displacements. In this case a knowledge of the boundary conditions and the stiffness is not necessary for estimating the stresses.

For beams with full rectangular cross-section and constant stiffness and weight loading, the following relationship applies, independent of the length, height and width of the beam, between the largest bending stress $\sigma_{\max}$ and the vibration velocity $\hat{v}_{\max}$:

$$\sigma_{\max} \approx \sqrt{E_{\text{dyn}} \rho} \times \sqrt{3 \frac{G_{\text{tot}}}{G_{\text{beam}}}} \times k_n \hat{v}_{\max}$$

where

$\hat{v}_{\max} = \hat{x}_{\max} \times \omega$ is the maximum amplitude of the vibration velocity occurring at a point at

the beam length [where ω is the forcing frequency approximately equal to ω_n (natural frequency of the beam)];

E_{dyn} is the dynamic elasticity modulus;

ρ is the mass density;

$\frac{G_{\text{tot}}}{G_{\text{beam}}}$ is the load coefficient, where the beam is stressed by other evenly distributed loads in addition to its own weight ($G_{\text{tot}} = G_{\text{beam}} + G_{\text{other loads}}$);

k_n is the mode coefficient (dimensionless), 1 to 1,33; the eigenmode coefficient k_n depends on the boundary conditions and the degree of the mode, which only has a slight influence.

For further details, see [18].

Annex C (informative)

Random data

C.1 General

Random data may be encountered in practice (wind loading, crusher machinery). Spectral analysis techniques can be used to estimate response characteristics. The estimate may be more or less precise depending on the structural characteristics (frequency and damping of a selected mode) and the precision required of the analysis.^[14] Two kinds of error, bias and variance, are involved. ^[14] Choice of recording duration depends on the permissible errors chosen. If bias error is to be 4 % and variance error 10 %, for example, the recording duration, T_r , in seconds, may be calculated using the following common formula:

$$T_r = \frac{200}{\eta f_n}$$

where

η is the modal damping ratio;

f_n is the natural frequency of mode n , under consideration, in hertz.

For instance, if $\eta = 1\%$ of critical and $f_n = 1$ Hz, then a recording duration of 20 000 s is needed to estimate to the bias and variance errors selected above. If η is 2 % of critical and f_n is 10 Hz, a recording duration of 1 000 s is needed. Acceptance of higher errors would reduce the required recording duration.

These requirements are independent of the type of equipment used for analysis. (It is common practice to use magnetic type recorders.) Structural damping

will be dealt with in a future addendum to this International Standard.

Non-stationary random data presents special problems and reference should be made to appropriate literature; see [14].

The analysis of random data is conducted in one of two domains, frequency and time, and these are considered in clause C.2 and clause C.3.

C.2 Frequency domain

In general vibration analysis, the quantity most often used is the Power Spectral Density (PSD). In the analysis of structural vibration, the amplitude spectral density itself may be presented. Other types of analysis in this domain include transfer function, cross PSD, coherence function, and quadrate spectral density. These results are presented as the "physical quantity" squared per hertz versus frequency, respectively as dimensionless numbers and ratios of physical quantities.

C.3 Time domain

In the time domain covariance, autocorrelation, cross-correlation, and covariance analyses may be carried out. The autocorrelation function, which is the inverse of the power spectrum, is the most commonly used. Many of the quantities in the time domain can be used with deterministic data. However, the more complex functions are often used with random data. Time-domain analysis covers mean, root-mean-square, peak counting, zero crossing counting as well as probability density, probability distribution, skewness and Kurtosis.

Annex D (informative)

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AMENDMENT 1

Page 17

Add the following annex as annex D and change the present annex D to annex E.

Page 18

Add references [24] to [38] to annex E.

Annex D

(informative)

Predicting natural frequencies and damping of buildings

Introduction

ISO 4866:1990 specifies methods of measuring building response including fundamental natural frequencies. When direct measurements cannot be made or are limited in usefulness by high damping, sub-component resonances or other practical problems, it becomes necessary to estimate natural frequency and damping values.

This annex offers guidance on the ways in which the fundamental natural frequency and associated damping value may be assessed. It draws attention to the uncertainties involved which should be taken into account wherever an estimation of fundamental natural frequencies of a building is used in measuring or evaluation procedures.

D.1 Predicting natural frequencies of tall buildings using empirical methods

There are many empirical formulae for predicting the frequency f , or period T , of the fundamental translation mode; of these the simplest is $f = 10/N$ Hz (i.e. $T = 0,1N$ s), where N is the number of storeys. Various other formulae are given in the codes of different countries and these can be grouped into three categories:

$$T = k_1 H \quad \dots \text{D.1}$$

where

H is the height, in metres;

T is the period, in seconds;

k_1 ranges from $0,14 \text{ sm}^{-1}$ to $0,03 \text{ sm}^{-1}$

(references [24] to [27]).

$$T = k_2 H \sqrt{D} \quad \dots \text{D.2}$$

where

D is the width parallel to the force, in metres;

k_2 ranges from $0,087 \text{ sm}^{-3/2}$ to $0,109 \text{ sm}^{-3/2}$

(references [25] and [28]).

$$T = k_3 H \sqrt{D} \text{ func}(H, D, I) \quad \dots \text{D.3}$$

(see, for example, reference [29]).

NOTE 1 k_1 has the units sm^{-1} ; k_2 has the units $\text{sm}^{-3/2}$.

A later study [30], considering a sample of 163 rectangular-plan buildings, recommended $f = 46/H$ Hz·m (i.e. $T = 0,022H \text{ sm}^{-1}$) for the fundamental translation mode, $f = 58/H$ Hz·m for the orthogonal fundamental translation mode and $f = 72/H$ Hz·m for the fundamental torsional mode (sample size of 63 buildings).

NOTE 2 These formulae for f are empirical. They may also be considered as numerical value equations yielding values of f in hertz when values of H in metres are inserted, for instance $f = 46/H$.

Figure D.1 shows the resulting fit of the curve $f = 46/H$ Hz·m to the data and it can be appreciated that large errors are likely to be encountered. It can be seen that errors of $\pm 50\%$ are not uncommon, and this is typical of the accuracy which can be expected using empirical formulae. Based on measured data, it appears that the mode shapes of the fundamental modes of tall buildings can be reasonably approximated by straight lines.

D.2 Predicting natural frequencies of tall buildings using computer-based methods

It has long been realised that comparatively large errors are likely to occur using the simple empirical formulae, but it has also been generally accepted that a satisfactory estimate of frequency can be obtained using one of the standard computer-based methods. However, buildings are complicated structures and it is not a simple task to create an accurate mathematical model; consequently it must be accepted that these models will only provide approximate predictions. In a study [30] examining published evidence, the correlation between computed frequencies and measured frequencies was actually considerably worse than the correlation between the frequencies predicted using $f = 46/H$ Hz·m and the measured values. This discrepancy can be attributed to inadequacies in modelling the real

properties of buildings. Predictions of fundamental frequencies should therefore be treated with caution.

Special methods have been developed for analysis of core buildings [31], shear buildings [32] and sway frame and frame buildings [33], but with any method it is important to check whether the method has been calibrated using a range of reliable experimental data and to understand what errors are likely to be encountered. If the method has not been proven, then accuracies greater than those obtained for empirical predictors should not be assumed. Only the fundamental frequencies have been discussed, but the predicted frequencies of higher frequency modes will suffer from similar or (more probably) greater errors. This means that, except for special cases where the mathematical model has been tuned to experimental results, predictions involving many calculated modes must be regarded as unreliable.

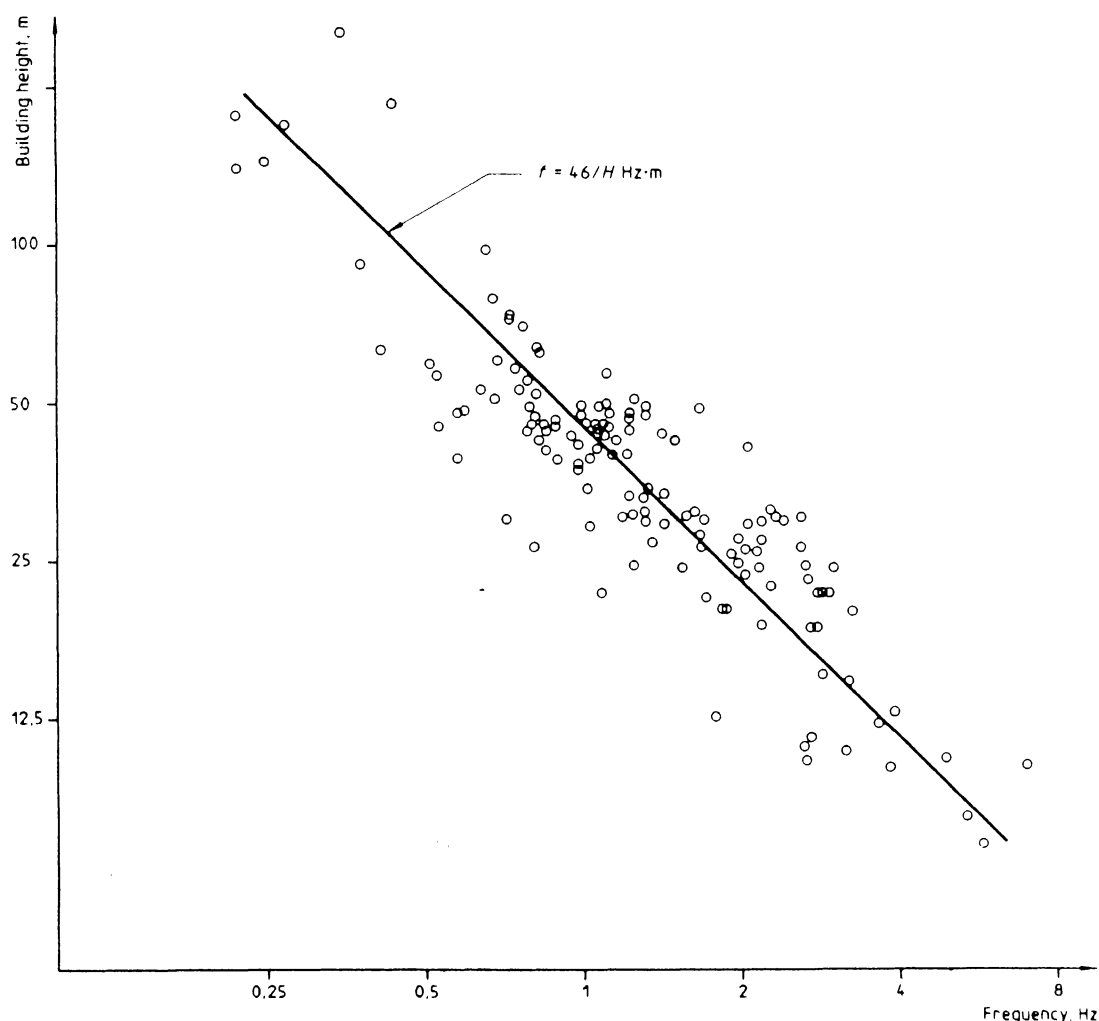


Figure D.1 — Plot of height versus fundamental frequency for 163 rectangular-plan buildings using logarithmic scales

D.3 Predicting damping values of tall buildings

The damping (or rate of energy dissipation) in any one mode limits the motion in that mode, and consequently to estimate the building response to a given load it is necessary to estimate or measure the amount of damping. No proven methods of predicting damping exist and the measured data show that damping values between 0,5 % and 2,1 % critical can occur (see figure D.2). Higher values may also be encountered in buildings where soil/structure inter-

action is significant. Simple steel frames are likely to have much lower damping. Methods of predicting damping have been developed (see refs. [34] and [35]) but, again, the expected accuracy is not quoted.

Figure D.2 shows a plot of damping versus building height for a selected sample of buildings [36]. It can be seen that large differences in damping can be obtained for orthogonal translation modes of the same building. Damping is partly a function of the construction procedures and workmanship involved and cannot be predicted accurately. Consequently, large errors in estimation must be anticipated.

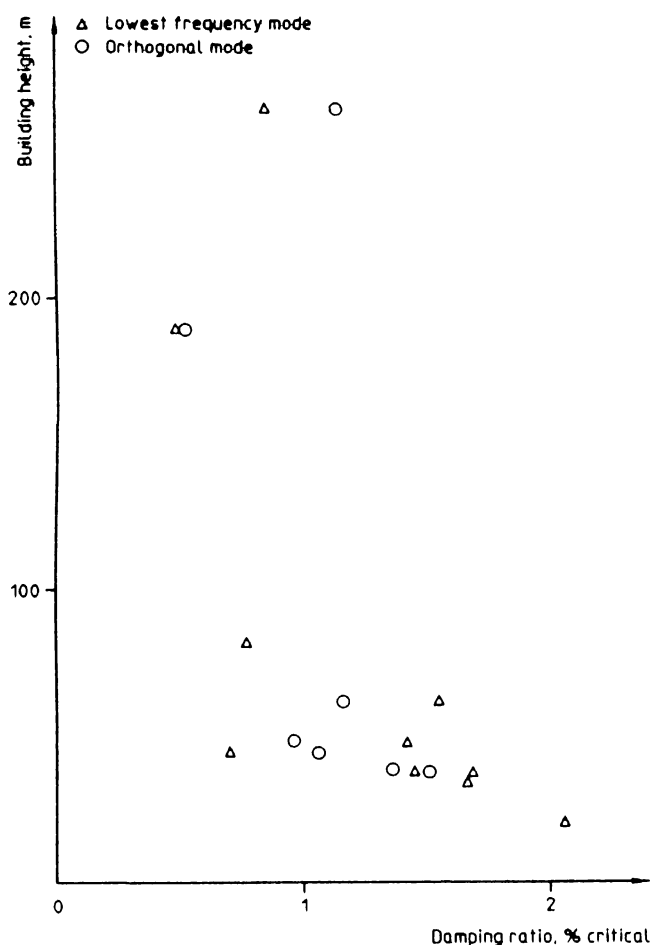


Figure D.2 — Building height versus damping ratio for the fundamental translation modes of 10 buildings where soil/structure interaction was negligible (from decay measurement)

D.4 Natural frequencies and damping values in low-rise buildings

The characteristics of 96 low-rise buildings are presented in references [37] and [38]. The buildings were located in the USA and are described as 1, 1½ and 2 storey buildings with basements, partial basements or crawl spaces. The data show that the average measured frequency decreases with building height.

Figure D.3 shows a histogram relating the number of buildings to their measured frequencies. It is important to note the range of frequencies which is encountered and thus the error involved in using an empirical prediction. There is no obvious tendency for the frequencies to vary with the age or location of the houses, and there is no correlation of the frequencies with plan dimensions.

Figure D.4 shows a histogram relating the number of buildings to their damping ratios. This indicates generally higher damping ratios than for taller buildings and shows the range of damping values which may be encountered. No obvious relationship between damping and building geometry exists.

D.5 Non-linear behaviour

The previous clauses discuss the natural frequency and the damping of each mode and this might give the impression that these quantities are invariant. However, they do vary with amplitude of motion and for earthquake analyses this might be important (albeit difficult to quantify). In general, wind loading induces small amplitude motion (in comparison with large earthquakes) and the changes in natural frequency and damping over the range of amplitudes normally encountered is small. In one building which was subjected to forces equivalent to a range of winds from light to hurricane force, changes of 3 % in frequency and 30 % in damping were recorded [36]. It can be appreciated that these changes are perhaps not significant and can be ignored for design purposes.

D.6 Final comment

The general conclusion which can be reached from this annex is that theoretical predictions are likely to involve considerable inaccuracies. Consequently, theoretical analyses should consider these possible inaccuracies by carrying out parametric variation and, for important structures, the design calculations should be verified using experimental measurements when the structure is complete.

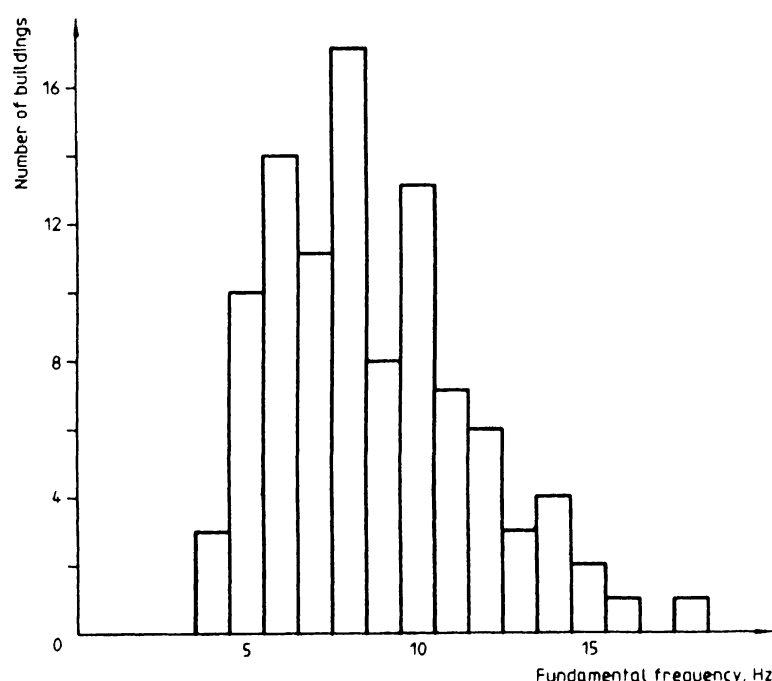


Figure D.3 — Frequencies measured in 96 low-rise buildings

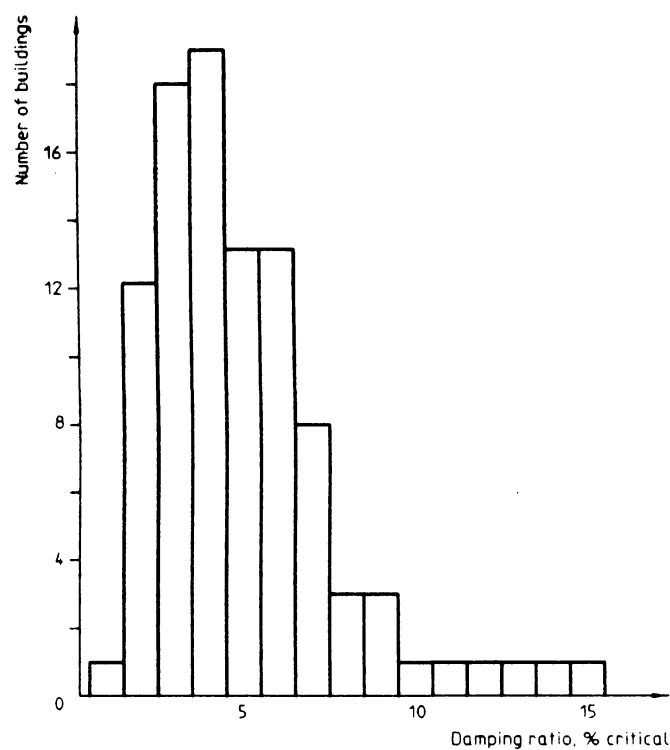


Figure D.4 — Damping ratios measured in 96 low-rise buildings

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